Deterministic Modeling of Water Entry and Drop of Mine-Shaped Bodies - An Essential Development for Stochastic Modeling

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Award Number: N00014-03-1-0059
http://web.mit.edu/spiral/www

LONG-TERM GOALS

The ultimate goal is to develop an effective physics-based simulation model that is capable of reliably predicting the motion of a mine-shaped object impacting water surface from air and subsequently dropping through water toward the sea bottom. This deterministic model provides the velocity and orientation of mines as the key input for bottom impact/burial prediction and is an essential building block in stochastic model development for mine burial predictions.

OBJECTIVES

- To model the dynamics of trapped air behind falling mines and its effect on the mine motion
- To model the complete six-degree-freedom motion of mines falling through water, including off-plan motion
- To improve the water-impact model to include free surface effects
- To perform systematic validations of the model by quantitative comparisons with tank and field drop test data

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Deterministic Modeling of Water Entry and Drop of Mine-Shaped Bodies - An Essential Development for Stochastic Modeling**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,,Department of Ocean Engineering,,Room 5-321, 77 Massachusetts Ave,,Cambridge,,MA,02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

- To assist the drop-test team (led by Dr. Phil Valent at Naval Research Laboratory (NRL)) in the design of experiments, and to transfer the simulation capability and results to the stochastic burial prediction team (led by Professor Alan Brandt at John Hopkins University (JHU)).

APPROACH

Two major physical problems are involved in the dynamics of trapped air behind falling mines: the air-trap during water entry; and the bubble oscillation and collapse after cavity closure. To model these problems, we carry out both analytical and numerical studies. At the first stage, the time and length scales of air-trapping are obtained by an analytic approach. At the second stage, a numerical method based on CFD techniques is used to investigate the bubble formation and collapse, and to parameterize the induced drag effects on the motion of falling mines.

To understand the mechanism of complicated mine motions observed in tank and field tests, we carry out a thorough study on directional instability of cylindrical bodies. It is found that the observed motions such as off-plan turning or spinning are resulted from the directional instability due to non-uniform flow environment. The key physical mechanisms causing such instability are investigated theoretically, and effective numerical models are developed and applied for the prediction of general motions of mines falling in water.

We study the free-surface effect in water impact of mines at low Froude numbers. To consider the real free-surface profile, the fully nonlinear numerical simulation based on the mixed Eulerian-Lagrangian approach ([1]) is applied. The nonlinear impact force as well as the evolution of the free surface is observed as time marches. Based on the complete fully nonlinear results, we improve and extend the present simplified water-impact models in the prediction of mine motions.

We perform systematic verification and calibration of the models by careful qualitative and quantitative comparisons with tank and field test data on motion patterns and motion kinematics including attitude, velocity and acceleration. Based on these validation and calibration, we continue to improve the accuracy and robustness of the models.

To ensure the success of this project, we collaborate closely with the complementary effort on the development of a stochastic burial prediction model at JHU and the tank/field test team at NRL. We provide guidance and technical support in hydrodynamics for the design of tank and field tests.

WORK COMPLETED

The major work completed includes:

- Complete analysis of directional stability for various motions observed in tank tests; investigation of the key mechanisms involved in motion instability; and development of proper numerical models to account for the instability effects in mine motion prediction

- Validation and calibration of the prediction model for the six degree-of-freedom motions of cylindrical bodies dropping through water; and qualitative/quantitative comparisons between our direct-simulation model predictions and the tank tests at NSWCCD

- Statistical analysis of mine motion dynamics, based on Monte-Carlo simulation with random parameters of mass center and initial release angle; and investigation on the statistical distribution of instantaneous and averaged velocity and attitude of mines

- Providing technical assistance in hydrodynamics to the mine drop test group at NRL in the design and conduction of tank and field drop tests, and collaborating with the stochastic burial prediction group at JHU.

RESULTS

Based on the analysis of motion stability, similar to the stability analysis of torpedo maneuvering, we found that the Munk moment plays an important role in the free-fall motions of cylindrical bodies. The directional change during vertical fall (vertical straight-slant motion), sudden directional turn during gliding motion (nose-turn motion), and development of yaw spinning in a short time (spiral motion) are critically dependent on the effect of the Munk moment. These motions are described by a single, two-, and three-coupled nonlinear equations, respectively. It is found that in the presence of small perturbations in body motion or environment, the free-fall motion becomes absolutely unstable for the cylindrical bodies without external devices or appendages. In particular, we identified the key mechanisms for the two distinct types of spiral motions observed in the tank tests. Significantly, the theoretical findings are confirmed by direct numerical simulations and experimental observations. After understanding the basic mechanisms of the distinct motion patterns, we developed effective models to predict these motions in realistic environment. Figure1 shows a sample simulation result of nose-turn and spiral motions of a cylindrical mine.

For the validation and calibration of the developed model ([2]), we compared our simulation results with the available experimental data obtained in tank and field tests. Overall, fair agreements between the predictions and experimental measurements are obtained. Figure 2 presents a sample comparison between the direct simulation and tank test data for the variation of the pitch angle during sea-saw motion of a cylindrical mine falling through water ([3]). The distinctive sea-saw features observed in experiments are well predicted by the direct simulation. However, it is difficult to obtain quantitative comparisons between the simulation and experiments due to the lack of information of uncertainties in experiments such as disturbances in ambient flow and the initial release conditions of the body.

For the prediction of mine motions in realistic environments, we conducted a statistical analysis based on Monte-Carlo simulation. The statistical representation of motion characteristics is an essential part of mine burial prediction, and also useful to complement the deterministic validation. Figure 3 plots a sample data set for the relation of the instantaneous velocity and pitch angle of the body at the water depth (five times of the body length). The result shows an approximately linear statistical relation between the two quantities. With such statistical analyses, we are able to identify the ranges of physical parameters for the occurrence of representative motion patterns.

IMPACT/APPLICATIONS

Proper modeling of the hydrodynamics of mines impacting the water surface and dropping through the water to the bottom is an essential building block in mine burial prediction. Our work provides a robust, reliable, and accurate model to predict the motion dynamics of cylindrical mines. Such accuracy and reliability cannot be achieved using the existing tools such as IMPACT 25/28.

TRANSITIONS

The present model developed in this study will be incorporated into a global prediction system of mine burial prediction. In particular, the hydrodynamic model will be used for the stochastic prediction of velocity and angle at ocean bottom, which is an essential input of soil-penetration prediction.

RELATED PROJECTS

This project is a part of mine burial prediction program (http://www.mbp.unh.edu/ front/index.cfm)

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[3] P. Valent & T. Holland, "Quick Look Report, Model Mine Hydrodynamics Tests, NSWC-Carderock, 10-14 Sep. 01", NRL Internal Memorandum, 2001.

PUBLICATIONS

Kim, Y., Liu, Y. & Yue, D.K.P. On the dynamics of a three-dimensional body falling through water, Journal of Fluid mechanics (submitted), 2003.

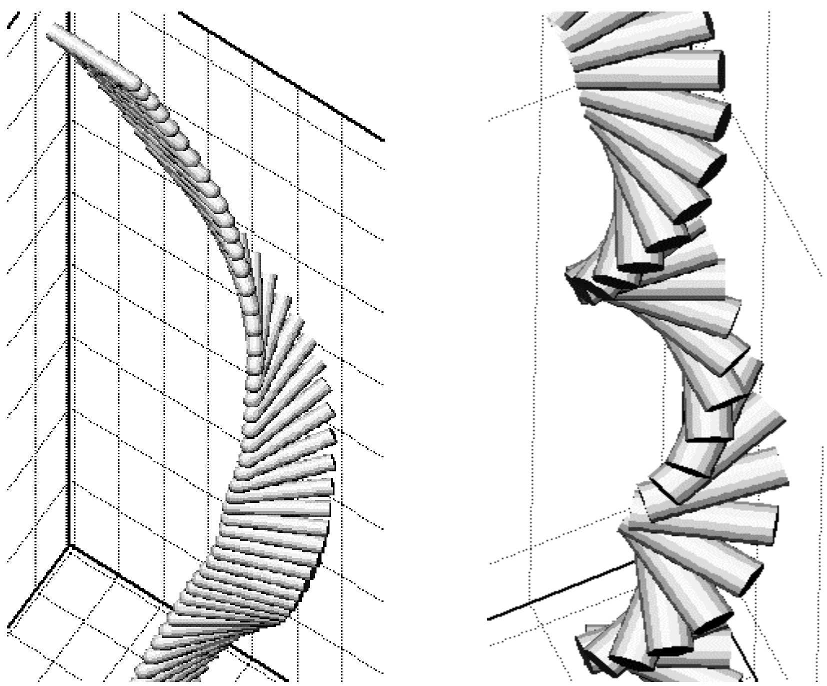

Figure 1. Motion trajectories of nose-turn (left) and spiral motions (right) of cylindrical mines: direct numerical simulation with a small perturbation of transverse velocity

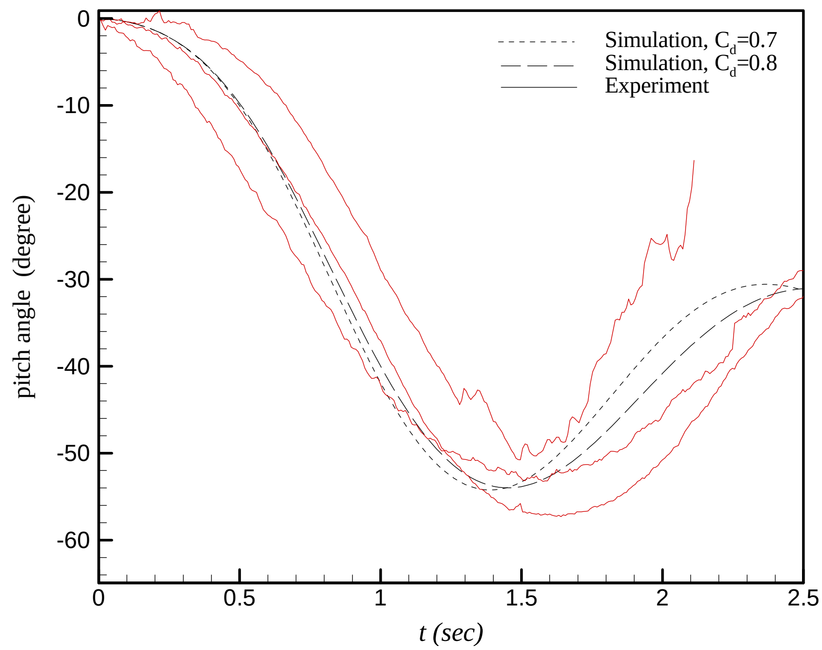

Figure 2. Comparison of the direct simulation (dashed lines) and tank experiment (solid line) for the time-histories of pitch angle during sea-saw motion of a horizontal cylindrical mine falling in water.

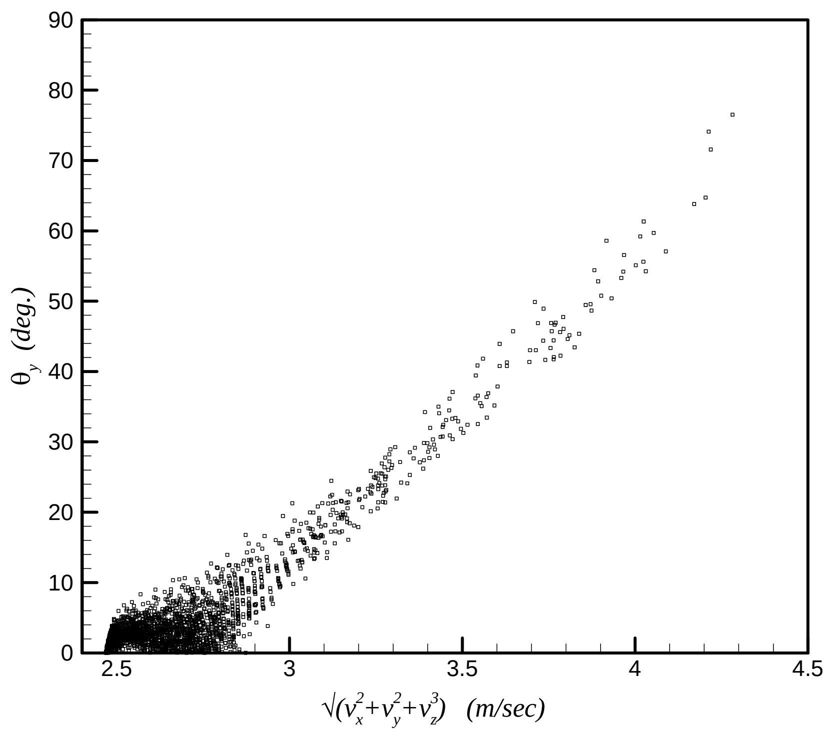

Figure 3. Statistical distribution of instantaneous velocity and pitch angle for a horizontal cylindrical mine falling in water at a particular water depth. The result is obtained using Monte-Carlo simulations with 2500 runs.